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An investigation into a contactless photoplethysmographic mobile application to record heart rate post-exercise: Implications for field testing

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Summary

Study aim: the aim of this study was to compare the accuracy of a contactless photoplethysmographic mobile application (CPA) to record post-exercise heart rate and estimate maximal aerobic capacity after the Queen's College Step Test. It was hypothesised that the CPA may present a cost effective heart rate measurement tool for educators and practitioners with limited access to specialised laboratory equipment.
Materials and Methods: seventeen participants (eleven males and six females, 28 ± 9 years, 75.5 ± 15.5 kg, 173.6 ± 9.8 cm) had their heart rate measured immediately after the 3-min test simultaneously using the CPA, a wireless heart rate monitor (HRM) and manually via palpation of the radial artery (MAN).
Results: both the CPA and MAN measurements had high variance compared to the HRM (CV = 31 and 11% respectively, ES = 1.79 and 0.65 respectively), and there were no significant correlations between the methods. Maximal oxygen consumption was estimated 17% higher in CPA compared to HRM ($p < 0.001$).
Conclusions: in conclusion it is recommended that field practitioners should exercise caution and assess the accuracy of new freely available technologies if they are to be used in practice.

Key words: Field testing – Heart rate – Mobile technology

Introduction

Aerobic capacity is a measurement important for those with an interest in sports performance as it can be used to prescribe training intensities and evaluate cardiovascular adaptations to training [5]. It is also of interest from a health and clinical point of view as it has been linked with both physical and mental health [2, 16]. To be measured accurately an aerobic capacity test is typically performed in a laboratory via the analysis of gaseous exchange. However there are times when this is not appropriate, and a barrier facing some practitioners in the field is that of the costs associated with laboratory testing.

There are numerous field based tests that can estimate aerobic capacity such as running tests (e.g. Cooper run), step tests (e.g. Harvard and Queens) and cycle ergometer tests (e.g Astrand-Rhyming and YMCA test). Such procedures provide an alternative method for individuals and/or practitioners with limited specialised equipment to monitor training efficacy. They also present an opportunity for teachers to implement physiological based fitness testing into taught sessions. The majority of these tests use heart rate recordings to estimate aerobic capacity via regression analysis. For some, collecting heart rate by manual arterial palpation may be the only option due to the costs associated with electrocardiograms (ECG), common heart rate telemetry straps and watches/other signal receivers. Such palpation methods have been deemed inaccurate by previous authors [6, 11].

The emergence of photoplethysmographic technology in mobile devices such as smart phones and tablet computers may present a more accurate cost effective alternative to manual methods. This technology uses the devices camera to measure subtle changes in skin colour [15]. Gregorski et al [7] reported high agreement between photoplethysmographic readings from a fingertip using a smartphone compared to an ECG at relatively low heart rates (70–80 bpm) during different activities (rest, reading

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aloud under observation and playing a video game). Ho et al [9] investigated the accuracy of four smartphone applications (Apps) to measure heart rate in children. They reported only moderate accuracy when taking photoplethysmographic readings from the ear lobe and relatively poor accuracy when readings were taken from the finger and toe. Furthermore the accuracy of the Apps reduced at higher heart rates (>120 beats per minute). In another study Wackel et al [18] also observed inconsistent accuracy at higher heart rates for two Apps taking fingertip readings.

In the afore mentioned studies the Apps relied upon skin contact, however some Apps offer a contactless alternative that observe colour video recordings of the human face [14]. Some authors have suggested that the contactless technology may be more accurate as the contact force between the sensor and measurement parts may affect the waveform of the signals [10]. A recent study [13] reported high accuracy for a mobile application using this contactless technology compared to a wireless heart rate monitor ($r^2 = 0.918$). Furthermore the accuracy of this application was higher than manual palpation of the radial artery ($r^2 = 0.851$). However this previous research was performed at rest and it is currently unclear whether this technology is sensitive enough to differentiate between beats at higher rates associated with exercise, which is pertinent considering the results from Ho et al [9] and Wackel et al [18].

The aim of this study was to assess the validity of a mobile application using contactless photoplethysmographic technology at higher heart rates, as it may present a cost effective option for individuals, educators and practitioners with limited access to specialised equipment.

Materials and method

Participant characteristics

Seventeen apparently healthy individuals volunteered for the study (eleven males and six females, 28 ± 9 years, 75.5 ± 15.5 kg, 173.6 ± 9.8 cm, body mass index 24 ± 2, training on average 4 times per week). The study was approved by an institutional ethics committee, and all participants gave written informed consent and were treated in accordance with the declaration of Helsinki.

Experimental design

Participants completed the Queen's College Step Test (QCST) which consisted of 3-min stepping at a rate of 22 and 24 steps · min^{-1} for females and males respectively, dictated by a metronome. This test has been validated against laboratory tests in previous research [1, 3], and was chosen as it can be completed with minimal technical equipment, so replicating the conditions in which the application may be of use. Immediately after the test heart rate was collected simultaneously by a wireless heart rate monitor (HRM; F11 Polar Electro, Finland), a freely available contactless photoplethysmographic App validated in previous work (CPA [13], Fig. 1) and manually from the radial artery (MAN).

These post-exercise values were then used to estimate aerobic capacity using the following equations [1]:

- *Males:* VO_2 max (ml/kg/min^{-1}) = 111.33 – (0.42 × heart rate)
- *Females:* VO_2 max (ml/kg/min^{-1}) = 65.81 – (0.1847 × heart rate)

Statistical analysis

All statistical analyses were completed using IBM SPSS Statistics 22 (SPSS Inc., Chicago, IL). Central tendency and dispersion of the sample data are represented as the mean ± SD. All data was normally distributed, as tested by Q-Q plots. Differences between CPA and MAN compared to HRM were analysed using an independent samples *t*-test with statistical significance set at $p < 0.05$. The relationship between the HRM and each other method was analysed using Pearson Correlation Coefficients, the coefficient of variation (CV) between measurements (standard deviation divided by the mean, multiplied by

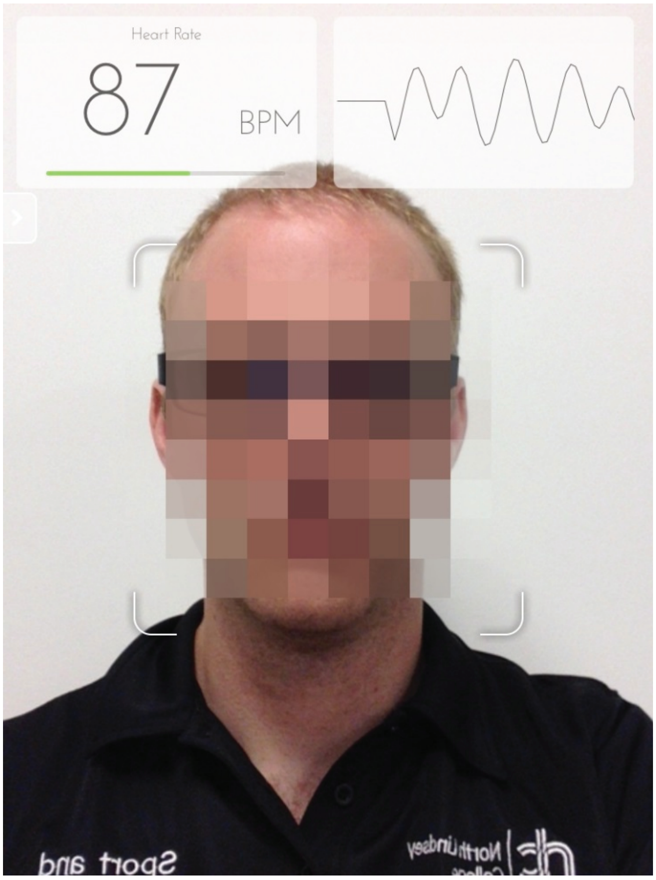

Fig 1. Screenshot of the CPA

Table 1. A comparison of post-exercise heart rate measured by MAN and CPA compared to HRM

	Average heart rate [bpm]	% difference	Average CV	ES	t	p
HRM vs. MAN	129 ± 19 vs. 115 ± 21	11.00	11.00	0.65	2.129	0.041
HRM vs. CPA	129 ± 19 vs. 84 ± 25	31.82	30.79	1.79	6.182	< 0.001

100) and the effect size (HRM minus MAN/CPA, divided by standard deviation of MAN/CPA). Bland-Altman plots were produced by plotting the differences between the two methods against the average. Differences between estimated maximal oxygen uptakes were analysed using a repeated measures ANOVA with Bonferroni corrected post-hoc tests.

Results

The average heart rate after the step test was significantly lower in MAN and CPA compared to the HRM control measure (Table 1). As a consequence VO_2 max was estimated 9% and 17% higher in MAN and CPA respectively compared to HRM ($P < 0.001$). The variances between the post-exercise heart rates are presented as Bland-Altman plots (Fig. 2 and 3), which identify that MAN measurements were less varied from HRM than CPA measurements.

There were no significant correlations between HRM and MAN ($r = 0.404$, $P = 0.108$) or HRM and CPA ($r = 0.441$, $P = 0.077$). However there were significant correlations between the HRM heart rate and the percentage differences between measurements (MAN $r = 0.498$, $P = 0.042$; CPA $r = 0.753$, $P < 0.001$), with a typically higher percentage difference as heart rate increased.

Discussion

The purpose of this study was to compare post-exercise heart rates recorded with a free mobile application (CPA) to a Polar heart rate monitor (HRM) to investigate

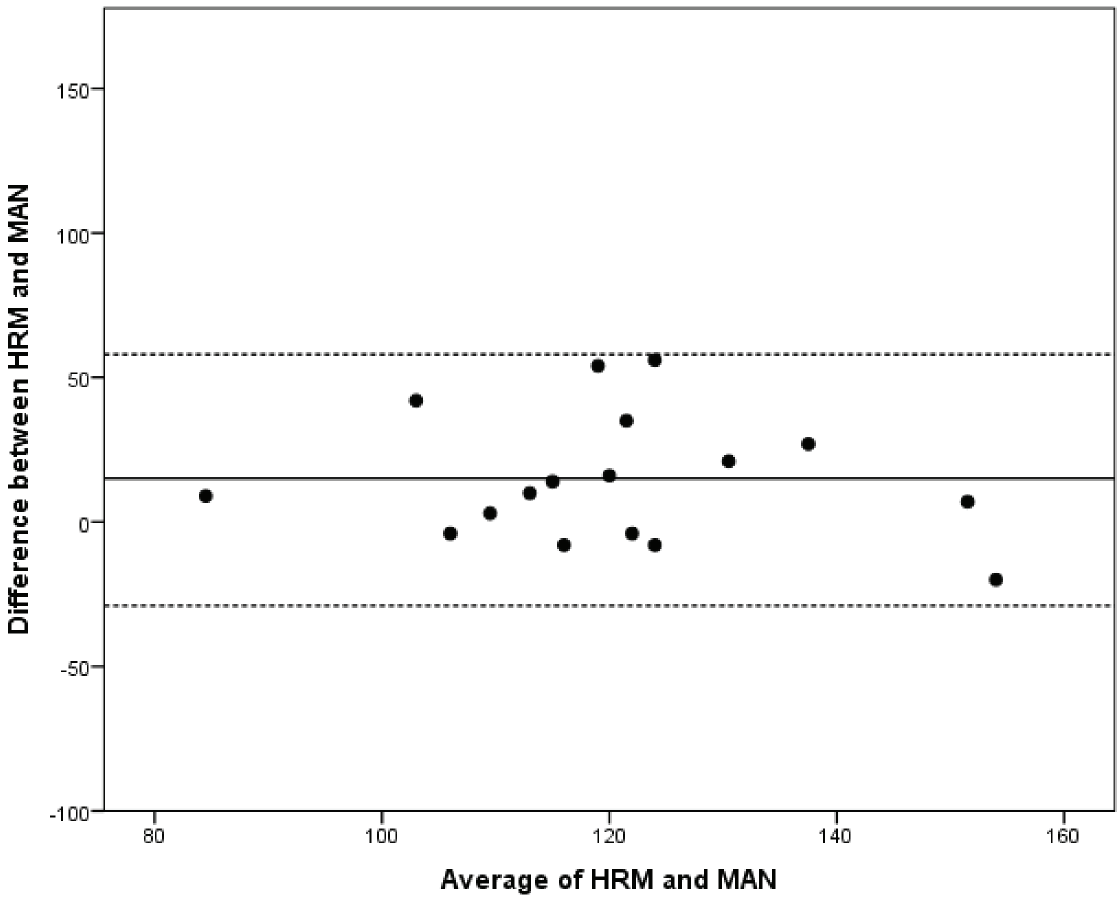

Fig 2. Bland-Altman plot for HRM compared to MAN

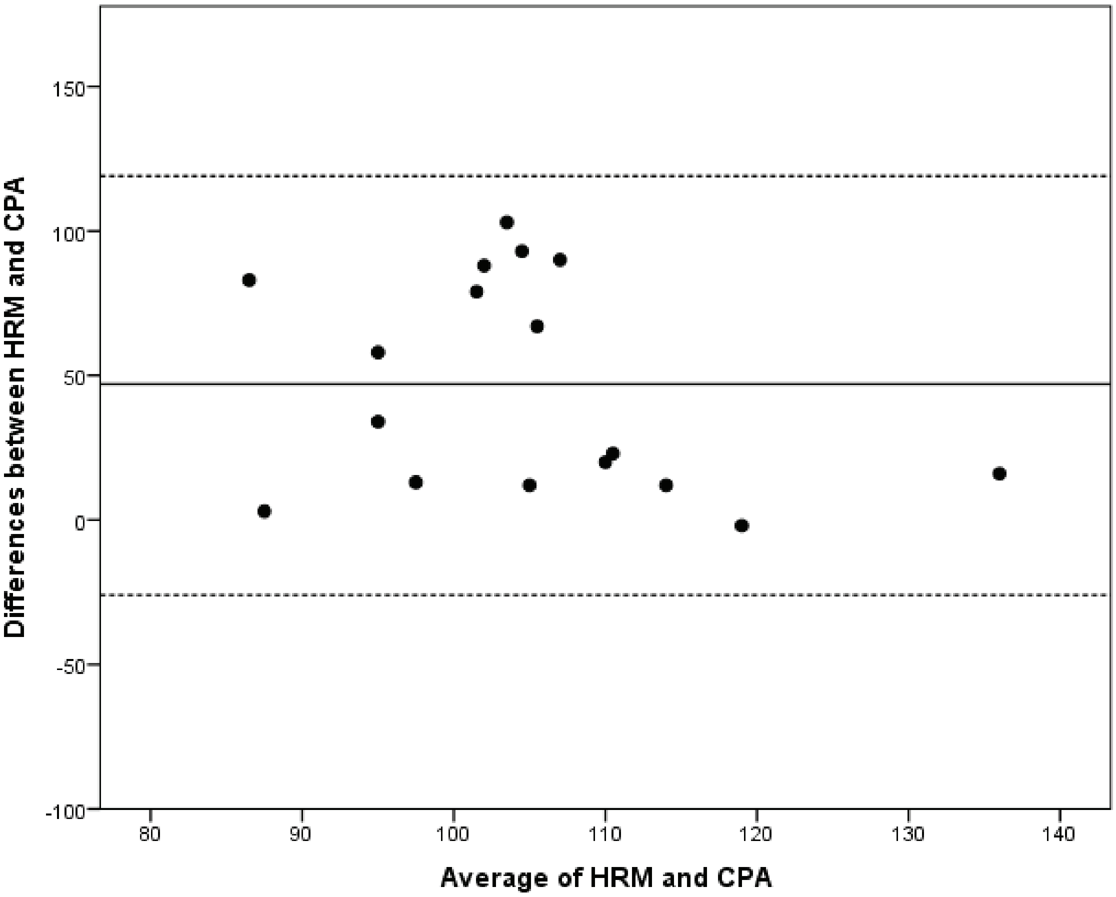

Fig 3. Bland-Altman plot for HRM compared to CPA

implications for field testing. It was found that the heart rate collected by the CPA was 31.82% lower than with the HRM, with some particularly large variance illustrated in Fig 3. Such disagreement between measurement tools would provide the practitioner or individual problems when interpreting results. For instance the data presented in this study results in the VO_2 max being estimated 17% higher following the QCST in the CPA compared to HRM.

Previous work [13] validated the CPA used in this study at rest. However other work has suggested that similar applications are not reliable at higher heart rates (i.e. after exercise), albeit using contact as opposed to contactless technology [9, 18]. The results from the current study suggest that the contactless technology in this particular App may also be less reliable at higher heart rates. Further support for this notion is given by the significant correlations between increasing heart rate and percentage difference between measurements i.e. variance increased as heart increased. Wackel [18] suggested that decreased accuracy at higher heart rates may relate to the processors used and a need for adapted programming to interpret the more frequent waveforms. They further suggested that the extent of participant movement may affect the accuracy of the technology. This cannot be discounted as changes in breathing rate post-exercise may have resulted in minor movements from the participants. However these suggestions are speculative at present as App development and software engineering are not within the scope of expertise of the research team.

Manual measurements also resulted in lower heart rates compared to HRM (Table 1), on average underestimating heart rate by 14 bpm and consequently estimating VO_2 max 9% higher than the HRM. Other studies have also criticised the use of manual palpation to measure post-exercise heart rate [4, 6]. However it must be considered that although the manual measurements were significantly different to HRM, the Bland-Altman plots and CV suggest that the results are not as varied as CPA. This suggests that whilst MAN may not be the most suitable method to measure post-exercise heart rate, it could be argued to be a better option than the CPA used in this study.

A wireless HRM monitor was used as a control in this study as it is representative of the highest level of technology likely to be available to practitioners in the field (i.e. gym/fitness instructors, personal trainers, coaches etc.).

However it is acknowledged that the validity of this study may have been improved with comparison to an ECG. Moreover actual maximal oxygen uptake was not assessed during this study, again due to the unlikelihood of a field practitioner having access to this type of data (hence the need for field tests). However the brand of HRM used in this study has been validated compared with an ECG [8, 12, 17], and the step test has been validated against laboratory tests [1, 3].

It is essential for the practitioner to appraise client/athlete progression with the most valid and reliable methods available in order to identify worthwhile changes in health and performance. Due to this it is advised that practitioners exercise caution when using free mobile applications to monitor physiological variables, particularly after exercise. Care must also be taken when using manual heart rate measurements, as although not as varied as the CPA, they still had unsatisfactorily high CV and ES.

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